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EDM constraints on flavored CP-violating phases

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- Outline

I- Introduction: MFV and CP-violating phases

II- MFV in the slepton sector

III- EDM constraints

Conclusion

L. Mercolli, C.S., ArXiv:0902.1949

Introduction

A. CP-violating phases in the MFV approach

MFV is based on the $U(3)^5$ *flavor symmetry group* of the gauge sector. *Chivukula, Georgi '87*

Minimally broken: such that quark and lepton masses/mixing are reproduced.

Technically, the Yukawas are treated as the only *spurions*.

All the *flavor-dependent couplings are hierarchical*, with their non-trivial structures inherited directly from those of the Yukawa couplings.

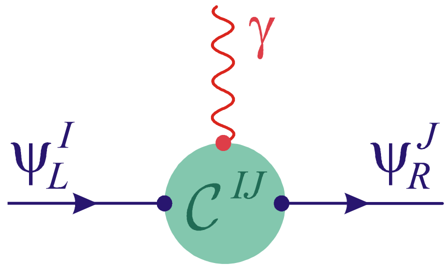
Hall,Randall '90, D'Ambrosio,Giudice,Isidori,Strumia '02

Does *this restrict CP-violating phases* only to those in the Yukawas? *No!*

- The $U(3)^5$ does not say anything about phases (*free param. are complex*),
- There can be new CP-violating *phases in other sectors*,
- Requiring MFV not to introduce new CP-phases is a *fine-tuning*.

B. Flavor transitions vs. flavor-diagonal observables

$$H_{eff} = e\frac{\mathcal{C}^{IJ}}{\Lambda^2}\bar{\psi}_R^I \sigma_{\mu\nu}\psi_L^J\, F^{\mu\nu} H_d$$



Flavor transitions ~ $\mathcal{C}^{I\neq J}$ are severely constrained by MFV:

In the quark sector, all flavor changes tuned entirely by the hierarchical CKM.

In the lepton sector, such transitions are forbidden as long as $m_\nu = 0$.

But for *flavor-diagonal* operators ~ $\mathcal{C}^{II}$, there is no restriction at all.

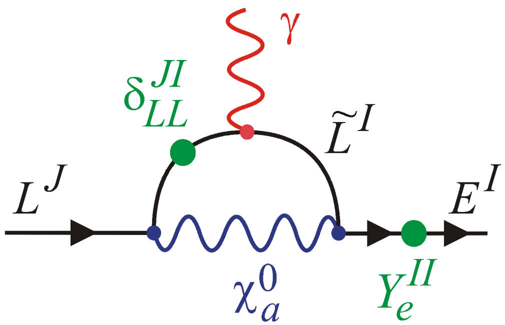
→ EDMs require very high New Physics scales?

C. Situation in the MSSM leptonic sector

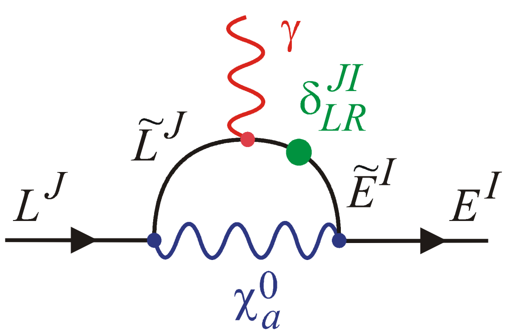
MFV implies expansions for the *soft-breaking couplings* in terms of Yukawa.

$$\mathcal{L}_{soft}^{RPC} \ni -\tilde{L}^{\dagger}\mathrm{m}_L^2\tilde{L} - \tilde{E}\mathrm{m}_E^2\tilde{E}^{\dagger} + \tilde{E}\mathrm{A}_e(\tilde{L}H_d) + \ldots$$

These can then *induce LFV transitions and EDMs*:



$$B(\ell^I \to \ell^J\gamma) \sim \frac{\alpha M_W^4 \tan^2\beta}{M_{SUSY}^4}\left|\delta_{LL}^{JI} + \ldots\right|^2$$



Beyond MFV

Correlations?

$$\frac{d_I}{e} \sim \frac{\alpha}{M_{SUSY}^3}\mathrm{Im}\left(m_\ell^I \mu\tan\beta - v_d \mathrm{A}_e^{*II}\right) + \ldots$$

MFV in the slepton sector

A. Construction of the MFV expansions

STEP 1: Identify the spurions, i.e. the *minimal sources of flavor breaking* able to reproduce known fermion masses & mixings (~ Yukawa).

Starting with $\mathcal{W}_N = N\mathbf{M}N + N\mathbf{Y}_\nu(LH_u) - E\mathbf{Y}_e(LH_d)$,

Cirigliano, Grinstein Isidori, Wise '05

Integrating out the right-handed (s)neutrinos:

$$\mathbf{Y}_e\,,\quad \mathbf{Y}_\nu^\dagger\mathbf{Y}_\nu\,,\quad \mathbf{Y}_\nu^T\mathbf{M}^{-1}\mathbf{Y}_\nu\,,\quad \mathbf{Y}_\nu^\dagger\mathbf{M}^{-1*}\mathbf{M}^{-1}\mathbf{Y}_\nu\,,\quad \ldots$$

$\mathbf{Y}_e$ → Lepton masses (diagonal)

$\mathbf{Y}_\nu^T\mathbf{M}^{-1}\mathbf{Y}_\nu$ → Neutrino masses (non-diagonal)

$\mathbf{Y}_\nu^\dagger\mathbf{Y}_\nu$ → Not completely fixed (we take $\mathbf{M} = M_R\mathbf{1}$):

$$\mathbf{Y}_\nu^\dagger\mathbf{Y}_\nu = \frac{M_R}{v_u}U^*\,\mathbf{m}_\nu^{1/2}e^{2i\Phi}\,\mathbf{m}_\nu^{1/2}U^\dagger\,,\quad \Phi^{IJ} = \varepsilon^{IJK}\phi_K$$

1 Dirac phase
2 Majorana phases
3 real ϕ_K parameters

→ *6 CP-phases*.

Casas, Ibarra '01
Pascoli, Petcov, Yaguna '03
Cirigliano, Isidori, Porretti '07

A. Construction of the MFV expansions

Nikolidakis,CS '07, Colangelo, Nikolidakis,CS '08, Mercolli, CS '09

STEP 2: Parametrize the *soft-breaking terms as expansions in the spurions*

- Most general expansions: $\mathrm{m}_L^2 = m_0^2 Q, \quad \mathrm{m}_R^2 = m_0^2(1+\mathrm{Y}_e Q \mathrm{Y}_e^\dagger), \ \mathrm{A}_e = A_0 \mathrm{Y}_e Q$

  with $Q = \sum z_{lmn\ldots} \mathrm{A}^l \mathrm{B}^m \mathrm{A}^n \ldots \qquad \mathrm{A} \equiv \mathrm{Y}_e^\dagger \mathrm{Y}_e, \ \mathrm{B} \equiv \mathrm{Y}_\nu^\dagger \mathrm{Y}_\nu$

- Reduced to a *finite number* of *hermitian* terms using Cayley-Hamilton identity:

$$\mathrm{X}^3 - \langle \mathrm{X} \rangle \mathrm{X}^2 + \tfrac{1}{2}\mathrm{X}(\langle \mathrm{X} \rangle^2 - \langle \mathrm{X}^2 \rangle) = \tfrac{1}{3}\langle \mathrm{X}^3 \rangle - \tfrac{1}{2}\langle \mathrm{X} \rangle \langle \mathrm{X}^2 \rangle + \tfrac{1}{6}\langle \mathrm{X} \rangle^3$$

- Use the large *mass hierarchy* to set $(\mathrm{Y}_e^\dagger \mathrm{Y}_e)^2 \sim \mathrm{Y}_e^\dagger \mathrm{Y}_e$, leaving:

$$Q = x_1 1 + x_2 \mathrm{A} + x_3 \mathrm{B} + x_4 \mathrm{B}^2 + x_5 \{\mathrm{A},\mathrm{B}\} + x_6 \mathrm{BAB}$$
$$+ x_7 i[\mathrm{A},\mathrm{B}] + x_8 i[\mathrm{A},\mathrm{B}^2] + x_9 i(\mathrm{BAB}^2 - \mathrm{B}^2\mathrm{AB})$$

If Q is hermitian: $x_i \in \mathbb{R}$, with x_{1-6} CP-conserving and $x_{7,8,9}$ CP-violating,

If Q is complex: $x_i \in \mathbb{C}$, all CP-violating. $\longrightarrow$ *15 CP-phases*.

B. CP-violation in the MFV framework

$$Q = x_1 1 + x_2 A + x_3 B + x_4 B^2 + x_5\{A,B\} + x_6 BAB + x_7 i[A,B] + x_8 i[A,B^2] + x_9 i(BAB^2 - B^2 AB)$$

Can we set and maintain $\mathrm{Im}\, x_{1-6} = 0,\ \mathrm{Re}\, x_{7,8,9} = 0$ in a natural way?

When the spurions are CP-violating, $\langle A^l B^m A^n ...\rangle$ can be complex:

- *Consistency*: Coefficients are understood to include spurion traces,
- *Choice of basis*: Coefficients differ by some spurion traces,
- *RGE effects*: Projecting back = absorbing spurion traces in the coefficients,

CP cannot be defined separately for the coefficients and for the spurions.

Forcing coefficients to conserve CP is *not protected by any symmetry*. Rather, it is, by definition, a *fine-tuning.*

B. CP-violation in the MFV framework

1- But it is a "*stable fine-tuning*":

When $Y_\nu^\dagger Y_\nu$ & $Y_e^\dagger Y_e$ are the only spurions, all complex traces → Jarlskog:

$$J = \mathrm{Im}\langle (Y_\nu^\dagger Y_\nu)^2 Y_e^\dagger Y_e Y_\nu^\dagger Y_\nu (Y_e^\dagger Y_e)^2 \rangle$$ …which is very small.

2- Same applies directly to the *quark sector*, with $A \equiv Y_d^\dagger Y_d, B \equiv Y_u^\dagger Y_u$.

3- Possible *fine-tuning mechanism* does exist, at least in the quark sector:

RGE effects suppress CP-phases (but |coefficients| are then constrained)

Paradisi,Ratz,Schieren,Simonetto '08, Colangelo,Nikolidakis,C.S. '08

4- CP-violating coefficients needed in the presence of *new spurions*:

$$(Y_\nu^\dagger Y_\nu)^{IJ} \quad , \quad \sum_K Y_\nu^{\dagger IK} Y_\nu^{KJ} \log M_R^{KK}$$

Ellis,Hisano,Raidal,Shimizu '08

C. Classification of the 6+15 CP-phases

Final expansions, with $a_i, b_i \in \mathbb{R},\ c_i, d_i \in \mathbb{C}$:

$$\mathrm{m}_L^2 = m_0^2(a_1 1 + a_2 \mathrm{A} + a_3 \mathrm{B} + a_5\{\mathrm{A},\mathrm{B}\} + a_6 \mathrm{BAB} + b_1 i[\mathrm{A},\mathrm{B}] + \mathcal{O}(\mathrm{A}^2,\mathrm{B}^2)),$$

$$\mathrm{m}_R^2 = m_0^2(a_7 1 + \mathrm{Y}_e(a_8 1 + a_9 \mathrm{B} + a_{11}\{\mathrm{A},\mathrm{B}\} + b_4 i[\mathrm{A},\mathrm{B}])\mathrm{Y}_e^\dagger + \mathcal{O}(\mathrm{A}^2,\mathrm{B}^2)),$$

$$\mathrm{A}_e = A_0 \mathrm{Y}_e(c_1 1 + c_2 \mathrm{A} + c_3 \mathrm{B} + c_5\{\mathrm{A},\mathrm{B}\} + d_1 i[\mathrm{A},\mathrm{B}] + \mathcal{O}(\mathrm{A}^2,\mathrm{B}^2))$$

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Flavor-blind phase: $\mathrm{Im}\, c_1$ (remember $d_I \sim \mathrm{Im}\,\mathrm{A}_e^{*II} \sim \mathrm{Im}\, c_1$)

Defined relative to the flavor-blind parameters of the MSSM ($\mu, M_1, M_2, \ldots$)

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Flavor-blind phase: $\mathrm{Im}\, c_1$

Defined relative to the flavor-blind parameters of the MSSM ($\mu, M_1, M_2, ...$)

Flavor-diagonal phases: $\mathrm{Im}\, c_{2-6}$ (remember $d_I \sim \mathrm{Im}\, \mathrm{A}_e^{*II} \sim \mathrm{Im}\, c_{2-6}$)

Contribute to EDMs at leading order in the MIA.

C. Classification of the 6+15 CP-phases

Final expansions, with $a_i, b_i \in \mathbb{R},\ c_i, d_i \in \mathbb{C}$:

$$\mathrm{m}_L^2 = m_0^2(a_1 1 + a_2 \mathrm{A} + a_3 \mathrm{B} + a_5\{\mathrm{A},\mathrm{B}\} + a_6 \mathrm{BAB} + b_1 i[\mathrm{A},\mathrm{B}] + \mathcal{O}(\mathrm{A}^2,\mathrm{B}^2)),$$

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Flavor-blind phase: $\mathrm{Im}\, c_1$

Defined relative to the flavor-blind parameters of the MSSM ($\mu, M_1, M_2, ...$)

Flavor-diagonal phases: $\mathrm{Im}\, c_{2-6}$

Contribute to EDMs at leading order in the MIA.

Flavor off-diagonal phases: $b_i, \mathrm{Re}\, d_i$, six phases of $\mathrm{Y}_\nu^\dagger \mathrm{Y}_\nu$ ⟵ (hermitian op.)

Start to contribute to EDMs at 2nd order in the MIA ($d_I \sim \mathrm{Im}(\delta_{LL}^{IK}\delta_{LR}^{KI}) + ...$).

EDM constraints

A. Dominant operators

Only a single operator dominates for $\mu \to e\gamma$ (coming from δ_{LL}):

$$B(\mu \to e\gamma) \sim \frac{\alpha M_W^4 \tan^2\beta}{M_{SUSY}^4} \left| \frac{a_3}{a_1} \left(\mathbf{Y}_\nu^\dagger \mathbf{Y}_\nu \right)^{12} \right|^2$$

Only a single operator per type of phases dominates for d_e:

$$\frac{d_e}{e} \sim \frac{\alpha m_e}{M_{SUSY}^2} \left(\frac{\operatorname{Im} c_1}{a_1 a_7} + \frac{\operatorname{Im} c_3}{a_1 a_7} \mathbf{Y}_\nu^\dagger \mathbf{Y}_\nu - \frac{b_1 \operatorname{Re} c_3}{a_1^2 a_7} [\mathbf{Y}_\nu^\dagger \mathbf{Y}_\nu, \mathbf{Y}_e^\dagger \mathbf{Y}_e] \mathbf{Y}_\nu^\dagger \mathbf{Y}_\nu + \ldots \right)^{11}$$

Flavor-blind — Flavor-diagonal — Flavor off-diagonal ($\geq$ neutrino phases)

Remark: $m_L^2 \approx m_0^2 a_1$, $m_R^2 \approx m_0^2 a_7$

A. Dominant operators

Only a single operator dominates for $\mu \to e\gamma$ (coming from δ_{LL}):

$$B(\mu \to e\gamma) \sim \frac{\alpha M_W^4 \tan^2\beta}{M_{SUSY}^4} \left| \frac{a_3}{a_1} \frac{M_R \Delta m_{21}}{v_u^2} \right|^2$$

Only a single operator per type of phase dominates for d_e:

$$\frac{d_e}{e} \sim \frac{\alpha m_e}{M_{SUSY}^2} \left(\frac{\operatorname{Im} c_1}{a_1 a_7} + \frac{\operatorname{Im} c_3}{a_1 a_7} \frac{M_R \Delta m_{21}}{v_u^2} - \frac{b_1 \operatorname{Re} c_3}{a_1^2 a_7} \frac{m_\tau^2}{v_d^2} \left(\frac{M_R \Delta m_{21}}{v_u^2} \right)^2 + \ldots \right)^{11}$$

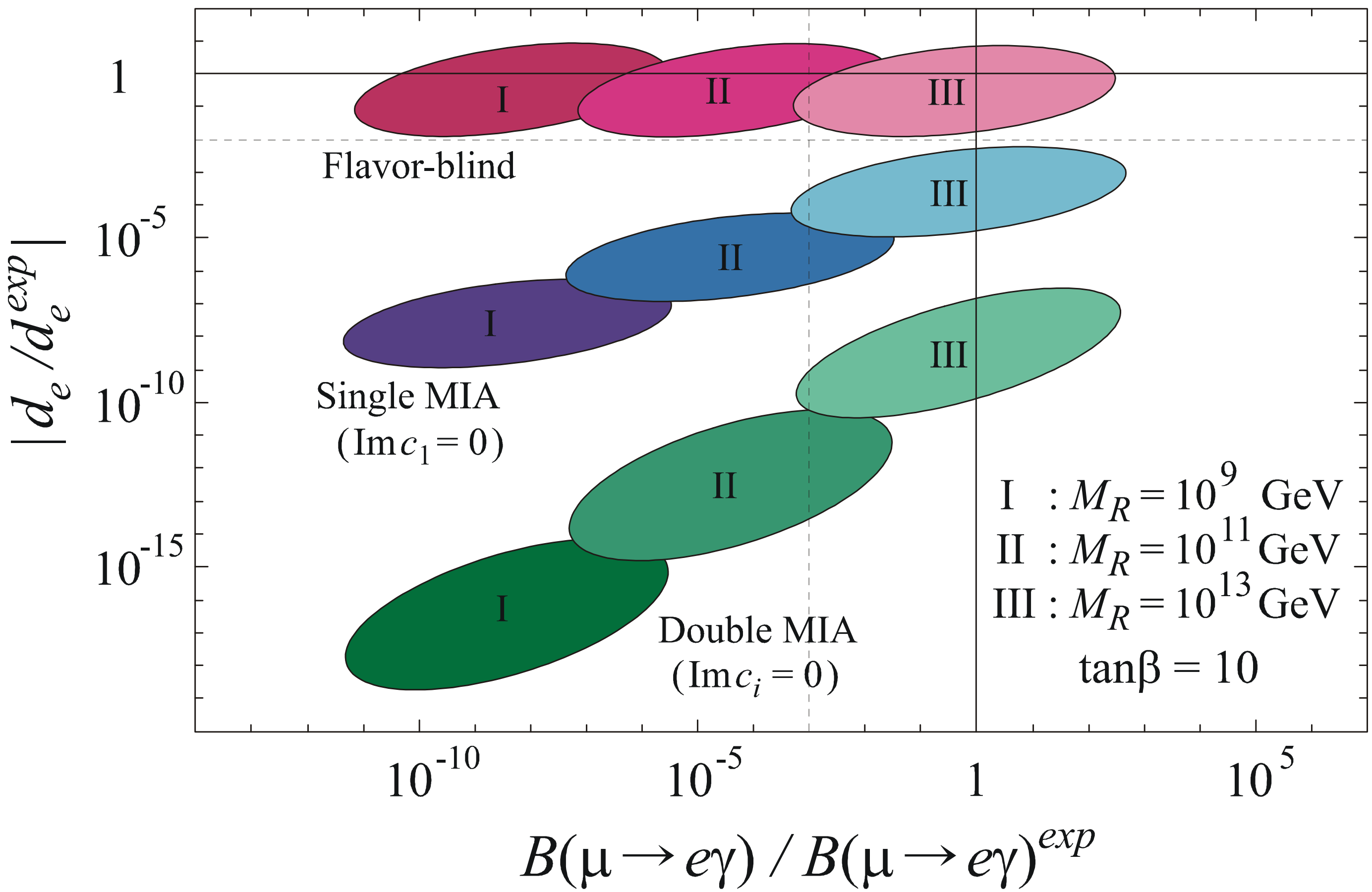
Flavor-blind $\gg$ Flavor-diagonal $\gg$ Flavor off-diagonal ($\geq$ neutrino phases)

$$M_{SUSY} \approx 500\, GeV$$

$$\Delta m_{21} \approx \sqrt{\Delta m_\odot^2} \approx 10^{-9} - 10^{-11}\, GeV$$

$$\Rightarrow M_R \leq 10^{13}\, GeV$$

A. Dominant operators



$$M_2 = \pm\mu = 2M_1 = \frac{2}{3} m_0 = A_0 = 400\,GeV\,,\ a_i, b_i, c_i, d_i \in \pm[0.1, 8]$$

B. Comparison with the model-independent approach

MSSM-inspired parametrization: $H_{eff} = e\frac{\alpha}{4\pi}\frac{(\mathrm{Y}_e Q)^{IJ}}{\Lambda^2}\,\bar{\psi}_R^I \sigma_{\mu\nu}\psi_L^J\, F^{\mu\nu} H_d$

where: $Q = h_1 1 + h_2 \mathrm{A} + h_3 \mathrm{B} + h_4 \mathrm{B}^2 + h_5\{\mathrm{A},\mathrm{B}\} + h_6 \mathrm{BAB}$

$+ g_1 i[\mathrm{A},\mathrm{B}] + g_2 i[\mathrm{A},\mathrm{B}^2] + g_3 i(\mathrm{BAB}^2 - \mathrm{B}^2\mathrm{AB})$

$(\mathrm{A} \equiv \mathrm{Y}_e^\dagger \mathrm{Y}_e, \mathrm{B} \equiv \mathrm{Y}_\nu^\dagger \mathrm{Y}_\nu)$

Flavor-blind: $\mathrm{Im}\, h_1$, for all flavor-blind parameters, including $\mu, M_1, M_2, ...$

Flavor-diagonal: $\mathrm{Im}\, h_{2-6}$, dominated by $\mathrm{Im}\, h_3$, LFV and EDM correlated.

Flavor off-diagonal: Do not contribute, $\mathrm{Y}_\nu^\dagger \mathrm{Y}_\nu$ phases have no impact.

Same general features, though $\Lambda \approx M_{SUSY}$ only up to a factor of ~ 5-10.

C. What about the general MSSM?

$$Q = x_1 1 + x_2 \mathrm{A} + x_3 \mathrm{B} + x_4 \mathrm{B}^2 + x_5 \{\mathrm{A},\mathrm{B}\} + x_6 \mathrm{BAB}$$
$$+ x_7 i[\mathrm{A},\mathrm{B}] + x_8 i[\mathrm{A},\mathrm{B}^2] + x_9 i(\mathrm{BAB}^2 - \mathrm{B}^2\mathrm{AB})$$

The MFV operators form a *complete basis* for soft-breaking terms.

Allowing the coefficients to take any value → *full MSSM*.

Experimental data $\Rightarrow$ *bounds on the coefficients*.

Turning on an operator $\Leftrightarrow$ Turning on a *whole set of mass insertions*, but with a definite pattern, originating from those of the spurions.

↓

Permits to test the *naturality* of soft-breaking terms.

C. What about the general MSSM?

m_L^2	(x_i / a_1)	m_R^2	(x_i / a_7)	$\mathrm{Re}\, A_e$	$(x_i / a_1 a_7)$	$\mathrm{Im}\, A_e$	$(x_i / a_1 a_7)$
a_1	*free*	a_7	*free*	$\mathrm{Re}\, c_1 \leq 10^2$	*stab.*	$\mathrm{Im}\, c_1 \leq 2$	d_e
$a_2 \leq 10^3$	*masses*	$a_8 \leq 10^3$	*masses*	$\mathrm{Re}\, c_2 \leq 10^3$	*stab.*	$\mathrm{Im}\, c_2 \leq 10^3$	*stab.*
$a_3 \leq 10$	$\mu \to e\gamma$	$a_9 \leq 10^6$	$\tau \to \mu\gamma$	$\mathrm{Re}\, c_3 \leq 10^3$	$\mu \to e\gamma$	$\mathrm{Im}\, c_3 \leq 10^3$	$\mu \to e\gamma$
$a_4 \leq 10^4$	$\mu \to e\gamma$	$a_{10} \leq 10^9$	$\tau \to \mu\gamma$	$\mathrm{Re}\, c_4 \leq 10^6$	$\mu \to e\gamma$	$\mathrm{Im}\, c_4 \leq 10^6$	$\mu \to e\gamma$
$a_5 \leq 10^3$	$\tau \to \mu\gamma$	$a_{11} \leq 10^7$	$\tau \to \mu\gamma$	$\mathrm{Re}\, c_5 \leq 10^5$	$\tau \to \mu\gamma$	$\mathrm{Im}\, c_5 \leq 10^5$	$\tau \to \mu\gamma$
$a_6 \leq 10^4$	$\mu \to e\gamma$	$a_{12} \leq 10^{11}$	$\tau \to \mu\gamma$	$\mathrm{Re}\, c_6 \leq 10^7$	$\mu \to e\gamma$	$\mathrm{Im}\, c_6 \leq 10^7$	$\mu \to e\gamma$
$b_1 \leq 10^3$	$\tau \to \mu\gamma$	$b_4 \leq 10^7$	$\tau \to \mu\gamma$	$\mathrm{Re}\, d_1 \leq 10^5$	$\tau \to \mu\gamma$	$\mathrm{Im}\, d_1 \leq 10^5$	$\tau \to \mu\gamma$
$b_2 \leq 10^6$	$\tau \to \mu\gamma$	$b_5 \leq 10^{10}$	$\tau \to \mu\gamma$	$\mathrm{Re}\, d_2 \leq 10^8$	$\tau \to \mu\gamma$	$\mathrm{Im}\, d_2 \leq 10^8$	$\tau \to \mu\gamma$
$b_3 \leq 10^8$	$\mu \to e\gamma$	$b_6 \leq 10^{13}$	$\tau \to \mu\gamma$	$\mathrm{Re}\, d_3 \leq 10^{10}$	$\mu \to e\gamma$	$\mathrm{Im}\, d_3 \leq 10^{10}$	$\mu \to e\gamma$

$$M_{SUSY} \approx 500\, GeV,\ \tan\beta = 20,\ M_R = 10^{12}\, GeV,\ m_{L,R} \leq 4\,\mathrm{TeV}$$

Compared to MIA: If a coefficient must be $x_i \gg 1 \Rightarrow$ *New flavor structures*

If a coefficient must be $x_i \ll 1 \Rightarrow$ *Fine-tuning problem is back*

If all coefficients are $x_i \approx 1 \Rightarrow$ *MFV*

Conclusion

MFV does introduce (many) CP-violating phases beyond those of the SM.

Rich CPV phenomenology, especially when two spurions are competitive.

Extension to the quark sector needs to be completed.

Is the “non-MFV” phase observed really beyond MFV?

Application to R-parity violating MFV:

Moderate M_R implied by $\mu \to e\gamma \Rightarrow$ Proton decay bounds easier to pass.

The only significant coupling, $\lambda''_{312}(t-s-d)$, is complex. Phenomenology?

Application to leptogenesis: Whole series of new CP-phase within MFV.